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PHYSICAL - CHEMICAL TREATMENT PLANT DESIGN

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PHYSICAL-CHEMICAL TREATMENT PLANT DESIGN

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INTRODUCTION

As illustrated by the previous paper by Cohen and Kugelman, the various approaches to physical-chemical treatment all involve the use of coagulation and settling for removal of suspended solids and, in some cases, phosphorus. Also, all involve the use of activated carbon for the removal of soluble organics. Some also involve the use of filtration for further removals of suspended solids and phosphorus.

The purpose of this paper is to discuss typical design parameters for the unit processes involved in physical-chemical treatment of raw wastes and how the design engineer may determine the design criteria best suited for a given wastewater.

PLANT PERFORMANCE SPECIFICATIONS

For purposes of providing an illustrative example, the raw waste characteristics and effluent requirements shown in Table 1 have been assumed. The effluent standards cannot be met with secondary treatment alone as chemical coagulation would be required to meet the phosphorus standard and, at least, filtration of a secondary effluent to meet the BOD and SS requirements. On the other hand, the effluent standards are not so stringent to know for certain that physical-chemical techniques must be used in series with biological treatment. Therefore, a design engineer faced with the above situation should conduct the necessary tests to determine if the above standards could be met by physical-chemical treatment alone and, if so, what design criteria should

TABLE 1

WASTEWATER CHARACTERISTICS AND EFFLUENT QUALITY REQUIREMENTS

	Influent, Average (mg/l)	Effluent, Weekly Average (mg/l)
BOD	180	15
COD	520	30
Suspended Solids	250	10
Hardness, as $CaCO_3$	150	-
Phosphorus	11.5	1
Alkalinity	220	-

be used. The unit processes involved are proven to the degree that extensive, on-site pilot tests are not necessary for most wastewaters and design criteria can be obtained in laboratory tests. Of course, if time and funds permit, an on-site pilot test over several months will permit an even more accurate determination of design criteria under a wider variety of operating conditions. Should on-site pilot studies be considered, the scale of the equipment can be tailored to meet the individual needs of the project. Small diameter filters and carbon columns (about 6-inch diameter) are adequate for column studies and can often be obtained from suppliers of carbon and filter manufacturers on a loan or rental basis. Pilot clarifiers of 6-10 feet in diameter can usually be rented from clarifier manufacturers. In a like manner, pilot sludge thickening and dewatering equipment can also be rented. The overall cost of pilot studies will vary widely depending upon the extent of the data collected. A meaningful study should span several months if any seasonal variations in raw wastewater quality are anticipated. Although pilot studies unquestionably provide a firmer basis of design, the author's experiences indicate that, except in unusual circumstances, the design criteria for the physical-chemical unit processes under consideration here can be determined with suitable accuracy in properly conducted laboratory tests on representative raw waste samples.

PRELIMINARY DATA COLLECTION

In order to proceed with the design on a rational basis, a characterization of the raw wastewater in terms of its amenability to physical-chemical treatment must be made. The following description of tests on a wastewater illustrate techniques which may be used. Four 24-hour composite samples collected during four different weeks are used in the example.

The goals of these tests are to answer the following major questions which must be answered before the design can proceed:

- What is the best coagulant?
- How much sludge is produced?
- How well does the sludge dewater?
- Is coagulant recovery practical?
- What is the nonadsorbable fraction of organics in the raw wastewater?
- How much carbon contact time will be required?
- What effluent quality can be expected?

SELECTION OF COAGULANT

There are four major classes of coagulants which may be considered singly or in combination:

1. Polymers. Some investigators have reported successful coagulation of raw sewage with polymers alone. The author has examined polymers as the primary coagulant on many wastewaters without finding them economically attractive when compared to the inorganic coagulants available. The cost of polymers is $1-$2 per pound. When used as the primary coagulant, polymers do not provide phosphorus removal. One of the following inorganic coagulants is required if phosphorus removal is of concern. Polymers used in conjunction with an inorganic coagulant are effective settling and filtration aids.

2. Iron Salts. Ferric chloride or ferric sulfate may be used for both suspended solids and phosphorus removal. Experience has shown that efficient phosphorus removal requires the stoichiometric amount of iron (1.8 mg/l Fe per mg/l of P) to be supplemented by at least 10 mg/l

of iron for hydroxide formation. Typically, 15-30 mg/l as Fe is required to provide phosphorus reductions of 85-90 percent. When considering iron for coagulation of raw wastes, it must be remembered that in an anaerobic environment, as may be encountered in a downstream carbon column, iron sulfide may be formed. This black precipitate is obviously not desirable in the final effluent.

3. Aluminum Salts. Both aluminum sulfate (alum) and sodium aluminate have been used for coagulation of wastewaters. Alum is generally a much more effective coagulant than sodium aluminate. Alum doses of 200-300 mg/l are typically required for 85-90 percent phosphorus removal (an aluminum to phosphorus ratio of 2-3). Disadvantages of both the iron and aluminum salts are (1) both form gelatinous hydroxide flocs which are difficult to dewater in many cases; (2) no techniques are available for recovery and reuse of the coagulant when phosphorus removal is required; and (3) large amounts of ions (chlorides or sulfates) are added to the wastewater.

4. Lime. Lime has been successfully used in several locales for wastewater coagulation and phosphorus removal. The amount of lime required is independent of the amount of phosphorus present; rather it is a function of the wastewater alkalinity and hardness. When the pH reaches 9.5 due to the addition of lime, the orthophosphate is converted to an insoluble form. In some cases, additional quantities of lime may be required to form a readily settleable floc. Lime has been recalcined and reused in some cases when used to coagulate secondary effluent. However, as will be illustrated later, recalcining and reuse may often not be practical when it is used to coagulate raw wastewaters due to the large

amount of inert materials present in the combined raw sewage-chemical sludges. In any case, lime sludges usually dewater more readily than those resulting from iron or aluminum coagulation.

The choice of coagulant can usually be made rather quickly by laboratory jar tests. The following illustrative example is based on data collected on a raw wastewater from a community in the midwest.

In the technique used, six one-liter samples are dosed with the coagulants being studied while being rapidly mixed with a jar test device. In this example, 0.5 mg/l of an anionic polymer (Nopcofloc 930, manufactured by Diamond Shamrock) was added as a settling aid. Following a 60-second rapid mix, the samples are slowly mixed for about 5 minutes. They are then allowed to stand quiescently to permit settling of the floc. Samples of the supernatant are then obtained with a pipette from a point just below the liquid surface in the jar. This is done to avoid including any of the floating solids which are invariably found in raw sewage. This supernatant sample is then analyzed for turbidity, pH, hardness (when lime is used as a coagulant), and phosphorus. A portion of the remaining supernatant is filtered through a Whatman No. 2 filter paper. The filtrate is analyzed for turbidity, phosphorus, and in some cases, TOC, COD, BOD, and suspended solids. Past experience has shown that the filtrate quality obtained with this filter paper will be about the same as that which will be achieved with a mixed-media filter.

Lime Coagulation

By plotting the jar test data, it was determined that the lime dosages required to achieve a filtrate phosphorus concentration of one mg/l were as follows:

Sample No. 1 = 132 mg/l as $Ca(OH)_2$
Sample No. 2 = 100 mg/l as $Ca(OH)_2$
Sample No. 3 = 110 mg/l as $Ca(OH)_2$
Sample No. 4 = 130 mg/l as $Ca(OH)_2$

One mg/l phosphorus was achieved at a pH of 9.1-9.5. The lime dosage required for optimum solids removal varied from 100-300 mg/l. In general, a somewhat higher dose of lime was required for optimum solids removal than was required for phosphorus removal. A lime dose of 200 mg/l achieved adequate solids removal for all four samples and this dose will be used in subsequent calculation of the cost of lime coagulation.

Suspended solids analyses showed that settled supernatant contained less than 5 mg/l suspended solids at this dose and the filtered supernatant generally contained no measurable suspended solids. A lime dose of 200 mg/l results in an effluent phosphorus concentration of 0.07-0.26 mg/l and a pH of 9.6-10.1. The lime and polymer dosage produced a rapidly settling floc, as it does in most wastewaters.

Alum Coagulation

The alum dosages required to achieve a filtrate phosphorus concentration of one mg/l were as follows:

Sample No. 1 = 120 mg/l
Sample No. 2 = 153 mg/l
Sample No. 3 = 165 mg/l
Sample No. 4 = 150 mg/l

The pH was reduced to 6.7-7.1 by the above alum dosages.

Adequate solids removal was achieved at alum doses equal to or less than that required for phosphorus removal.

Iron Coagulation

The ferric chloride dosages required to achieve a filtrate phosphorus concentration of one mg/l were as follows:

Sample No. 1 = 20 mg/l as Fe
Sample No. 3 = 27 mg/l as Fe
Sample No. 4 = 23 mg/l as Fe

The required Fe/P ratios were 2.7, 2.4, and 2.5 respectively. It appeared that the dose required for phosphorus removal would equal or exceed that required for solids removal.

Comparison of Coagulant Costs

The cost of the various coagulants at the plant site is as follows:

Lime = $16.75/ton of CaO
Alum = $70/ton
Ferric Chloride = $90/ton (or $262/ton of Fe)

The estimated costs for coagulation with the following doses are as follows:

200 mg/l lime [as $Ca(OH)_2$] = $10.60/mg
160 mg/l alum = $46.50/mg
23 mg/l Fe = $25.10/mg

It is apparent that lime is the lowest cost coagulant, even when the lime dosage involved reduces the phosphorus to less than 0.3 mg/l.

Of course, the total economic comparison must also include the relative cost of sludge disposal associated with each coagulant. Nearly always the lime sludges may be disposed of at significantly lower costs than the sludges resulting from either alum or iron coagulation. Thus, in the above example, there is little doubt that lime will remain the most economical coagulant when sludge disposal costs are included.

The general dewatering characteristics of the sludge may be determined by laboratory tests. A 100 ml sludge sample is dewatered with a Whatman No. 2 filter paper in a Buchner funnel with laboratory vacuum. The volume of filtrate versus time is then plotted and compared to similar data for sludges for which field experience has also been obtained. Figure 1 presents an example comparison which shows that the sludges resulting from coagulation of this wastewater dewatered even more readily in the lab than did another sludge which later proved to dewater very well in a centrifuge. Thus, the dewatering of the sludge does not appear to be a limiting factor in this case.

It is difficult to obtain an accurate gravimetric measurement of sludge quantities in a laboratory test due to loss of solids during decanting, etc. However, it is possible to estimate the quantities of lime sludge from the chemistry involved and the data collected from the jar tests. As shown in Table 2, about 4,050 pounds of solids per million gallons would be expected with a lime dose of 200 mg/l. Following incineration, the ash quantities would be about 2,165 pounds per million gallons.

With this information, it is then possible to determine the feasibility of recalcining and reusing the lime. From Table 2, it is apparent that if one were to recycle all of 820 pounds of the lime recovered per mg, that one would also recycle 1,345 pounds of inert ashes. Assuming that a 20 percent blowdown were practiced, one would recycle 670 pounds lime and 1,080 pounds inerts. After the second cycle, there would now be 1,345 + 1,080

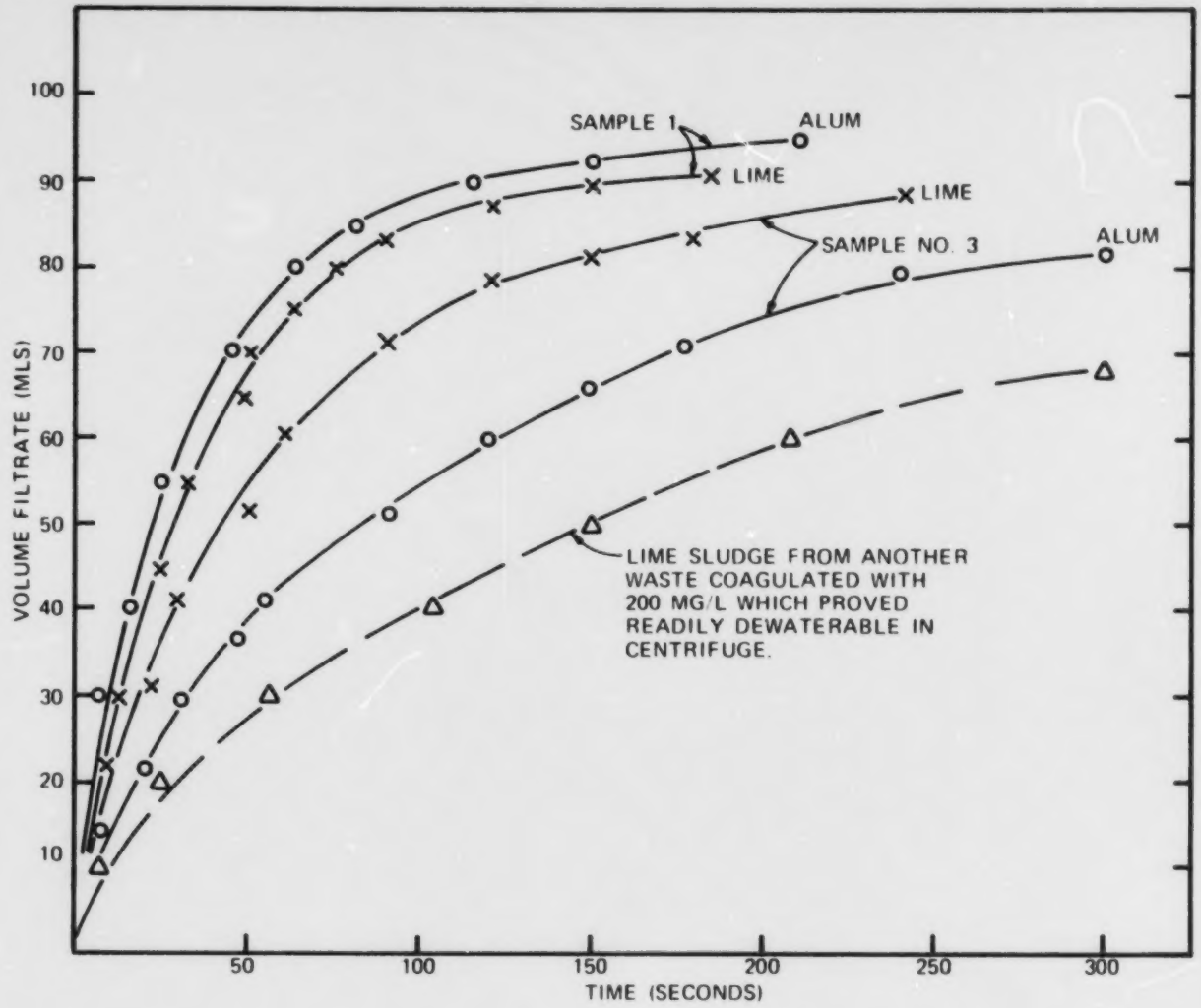

FIGURE 1

SLUDGE DEWATERING CHARACTERISTICS

TABLE 2

ESTIMATE OF LIME SLUDGE QUANTITIES

Raw Sewage Suspended Solids = 250 mg/l

Raw Sewage PO_4 = 34.5 mg/l

Add 200 mg/l lime as $Ca(OH)_2$ or 108 mg/l Ca

Assume all 250 mg/l raw sewage SS removed

Assume lime reacts with PO_4 to form

$Ca_5(OH)(PO_4)_3$

Weight of $Ca_5(OH)(PO_4)_3$ formed =

$$\frac{Ca_5(OH)(PO_4)_3 \text{ m.w.}}{(PO_4)_3 \text{ m.w.}} \times PO_4 \text{ conc} = \frac{502}{285} \times 34.5 = 61 \text{ mg/l}$$

Raw Hardness = 150 mg/l as $CaCO_3$ [as measured on Sample No. 4 with 200 mg/l $Ca(OH)_2$]

Treated Hardness = 185 mg/l as $CaCO_3$

Ca lost in effluent = $\frac{40}{100} \times (185-150)$ = 14 mg/l

Ca in $Ca_5(OH)(PO_4)_3$ = $\frac{200}{502} \times 61$ mg/l = 24 mg/l

Ca in $CaCO_3$ sludge = 108 - (24 + 14) = 70 mg/l

Quantity of $CaCO_3$ = $\frac{100}{40} \times 70$ = 175 mg/l

Sludge Composition						Ash
Raw Sewage Solids	= 250 mg/l	= 2080 lbs/mg	x	.4	=	835 lbs/mg
$Ca_5(OH)(PO_4)_3$	= 61 mg/l	= 510 lbs/mg	x	1.0	=	510 lbs/mg
$CaCO_3$	= 175 mg/l	= 1460 lbs/mg	x	.56	=	820 lbs/mg
		4050 lbs/mg				2165 lbs/mg

pounds of inerts in the furnace discharge or 2,425 pounds of inerts. Table 3 presents an illustrative calculation of the buildup of inerts through 11 cycles with 20 percent blowdown of the furnace product.

Eventually, one will be dewatering and incinerating about 6,500 pounds of inerts per mg in order to recover only 670 pounds of lime. The solids handling system would have to be sized for a solids load corresponding to a nonvolatile fraction of about 7,300 pounds/mg rather than the 2,165 pounds/mg if the sludge was merely incinerated and thrown away. One would be spending far more to recover the lime than it would be worth. A higher blowdown rate still does not make recalcining practical in this example. It is far cheaper to use the lime once and dispose of the sludge. Until a means is available for very efficient separation of lime from the inerts in the combined raw sewage-chemical sludge, lime recycle will often not be practical when coagulating raw sewage unless very high lime doses are involved. Envirotech is developing a dry classification technique for this purpose but no data are yet available.

CARBON ADSORPTION

There are organics (i.e., sugars) which may be readily biodegradable but which are very difficult to adsorb on carbon. The amount of these nonadsorbable materials will vary greatly from wastewater to wastewater and their presence will be the governing factor concerning the quality of effluent which can be achieved by carbon adsorption. The same physical-chemical process may produce a BOD of 10 mg/l in one locale and 30 mg/l in another due to this fact. The ability to remove the soluble organics may be measured in the laboratory by two methods.

One of these is a batch process in a beaker while the other is a flow-through, carbon column experiment. In the first case,

TABLE 3

EFFECT OF RECYCLING RECALCINED MATERIALS

	Pounds per Million Gallons			
	Furnace Discharge		Recycled Material with 20% Blowdown	
Cycle No.	Lime	Inerts	Lime	Inerts
1	820	1345	670	1080
2	820	2425	670	1940
3	820	3285	670	2630
4	820	3975	670	3180
5	820	4525	670	3620
6	820	4965	670	3970
7	820	5315	670	4250
8	820	5595	670	4480
9	820	5825	670	4660
10	820	6005	670	4800
11	820	6145	670	4915
-	--	--	--	--
-	--	--	--	--
-	--	--	--	--

Assumes 100% calcium recovery from sludge and makeup lime to maintain 200 mg/l lime dose

the raw sewage is contacted with 1,000 mg/l of Aqua Nuchar A, a powdered carbon, for one hour. Alternately, a sample of the granular carbon under consideration may be ground and applied to the sample. The sample is then coagulated, settled, and the supernatant filtered through Whatman No. 2 filter paper prior to analysis. Past work with powdered carbon indicates that an Aqua Nuchar dose of 600 mg/l and a contact time of five minutes is generally adequate for removal of all adsorbable organics. Thus, the above conditions insure that all adsorbable materials are, in fact, removed. The above technique is a quick method of determining the nonadsorbable fraction of organics. The isotherm technique which will be described by Mr. Rizzo will provide more information.

The column tests may be conducted using Calgon Filtrasorb 400 carbon or equivalent in five 3/4-inch diameter columns in series. The columns are sized so that cumulative contact times of 7.5, 15, 30, 45, and 60 minutes are provided at the end of the respective columns. Four to five gallons of raw sewage are coagulated with either lime or alum, settled, the supernatant decanted (the pH adjusted to 7 when lime is used), and the clarified wastewater pumped through the columns. This quantity of sewage will provide several days of operation in columns of this size. The tests should be continued as long as possible to accurately determine the effects of biological activity. The sludge should be saved for analysis. The results from these small columns have been found by the author to be consistent with those obtained in larger units. For example, in one study spanning several months, the results concerning contact time from small laboratory columns in the first four weeks of the study were essentially the same observed from both 6-inch diameter and 3-foot diameter columns operated over several months.

The reasons for preferably conducting both the powdered carbon and column tests are to determine if the effluent from the columns

could be lower in BOD than that achieved by adsorption alone due to the biological growth in a column and to determine the effects of contact time on column performance.

Powdered Carbon Results

The effluent quality achieved by the powdered carbon technique above should closely represent the nonadsorbable fraction of the organics contained in the raw waste samples tested. The results obtained with the wastewater in question are as follows:

	Sample No.			
	1	2	3	4
COD, mg/l	21	30	44	16
BOD, mg/l	12	17	18	2
TOC, mg/l	6	12.5	15	6
COD/TOC	3.5	2.4	2.9	2.7
COD/BOD	1.74	1.76	2.4	8

The three parameters show similar trends from sample to sample with the fourth sample containing substantially less nonadsorbable organics than Samples 2 and 3 and somewhat less than Sample 1. It appears that the BOD of 2 mg/l measured for Sample 4 may be low as the COD/BOD ratio is considerably out of line with the other samples. The COD appears valid as the COD/TOC ratio compares closely with the other samples. However, it is possible that there was a change in the nature of the unadsorbable organics so that, in fact, a smaller portion was biodegradable.

The nonadsorbable BOD ranged from 2-18 mg/l with an average of 12.2 mg/l for the four samples.

Column Tests

Figures 2 and 3 summarize the data collected from the laboratory columns. As can be seen from the figures, the benefits achieved by contact times greater than 30 minutes are slight. The carbon column effluent BOD values after 60 minutes contact ranged from 5 to 15 mg/l and averaged 11.0 mg/l. The BOD samples collected at a 30-minute contact time averaged 12.5 mg/l.

An estimate of the required carbon dosage can be made by assuming that carbon will be withdrawn for regeneration when the carbon loading is 0.5 pounds of COD removed per pound of carbon. This loading has been achieved in several studies. An average soluble influent COD of 86 mg/l was achieved with lime clarification in the four series of jar tests. The average COD achieved in the four powdered carbon tests was 23 mg/l and averaged 24 mg/l after 30 minutes contact in the columns. Thus, an average COD removal of about 62 mg/l would be expected from these tests. The corresponding carbon dosage is 1,030 pounds/mg. Carbon dosages calculated from short-term laboratory column tests are usually conservatively high, as biological action usually results in greater permissible loadings in a continuous, plant scale operation.

PROCESS DESIGN

The purpose of this section is to discuss those design criteria necessary for plant design. Figure 4 illustrates the flow sheet upon which the following discussion is based.

Flow

Both the average and peak flows are of concern. In a physical-chemical plant, there is a substantial volume of flow recycled to the head of the plant from the following major sources: (1) furnace scrubber underflow, (2) filter and activated carbon

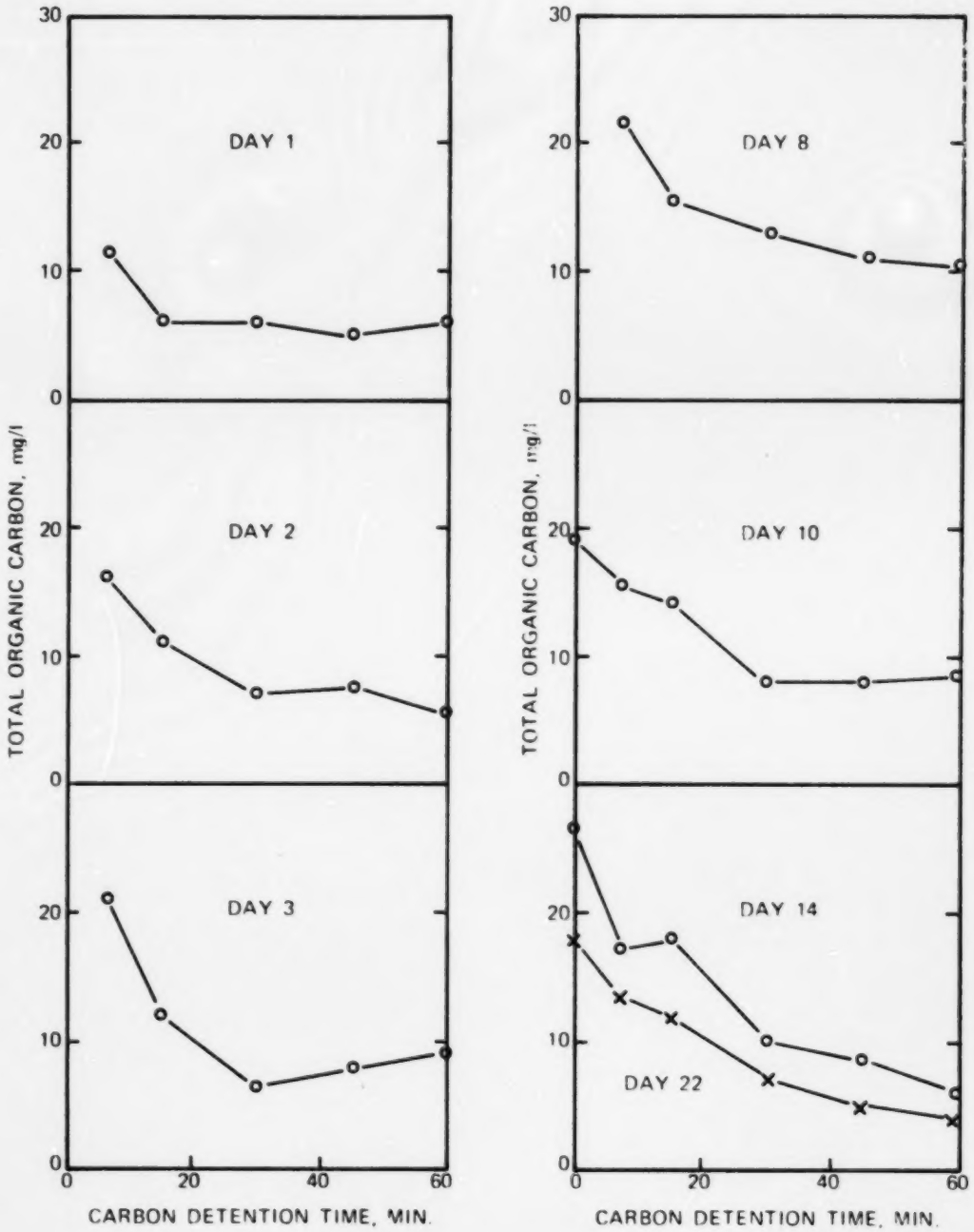

FIGURE 2

PILOT CARBON COLUMN DATA

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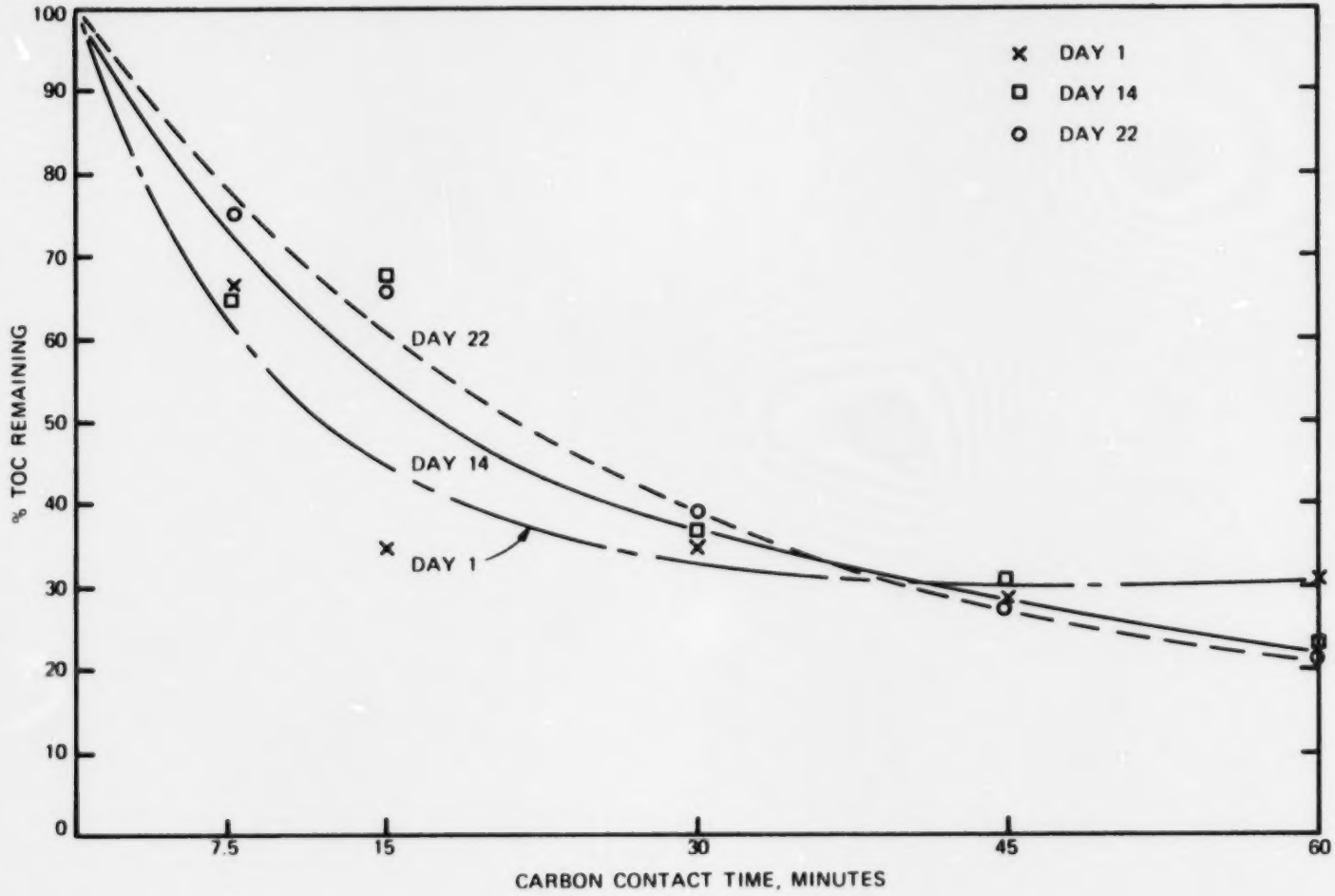

FIGURE 3

PILOT CARBON COLUMN DATA

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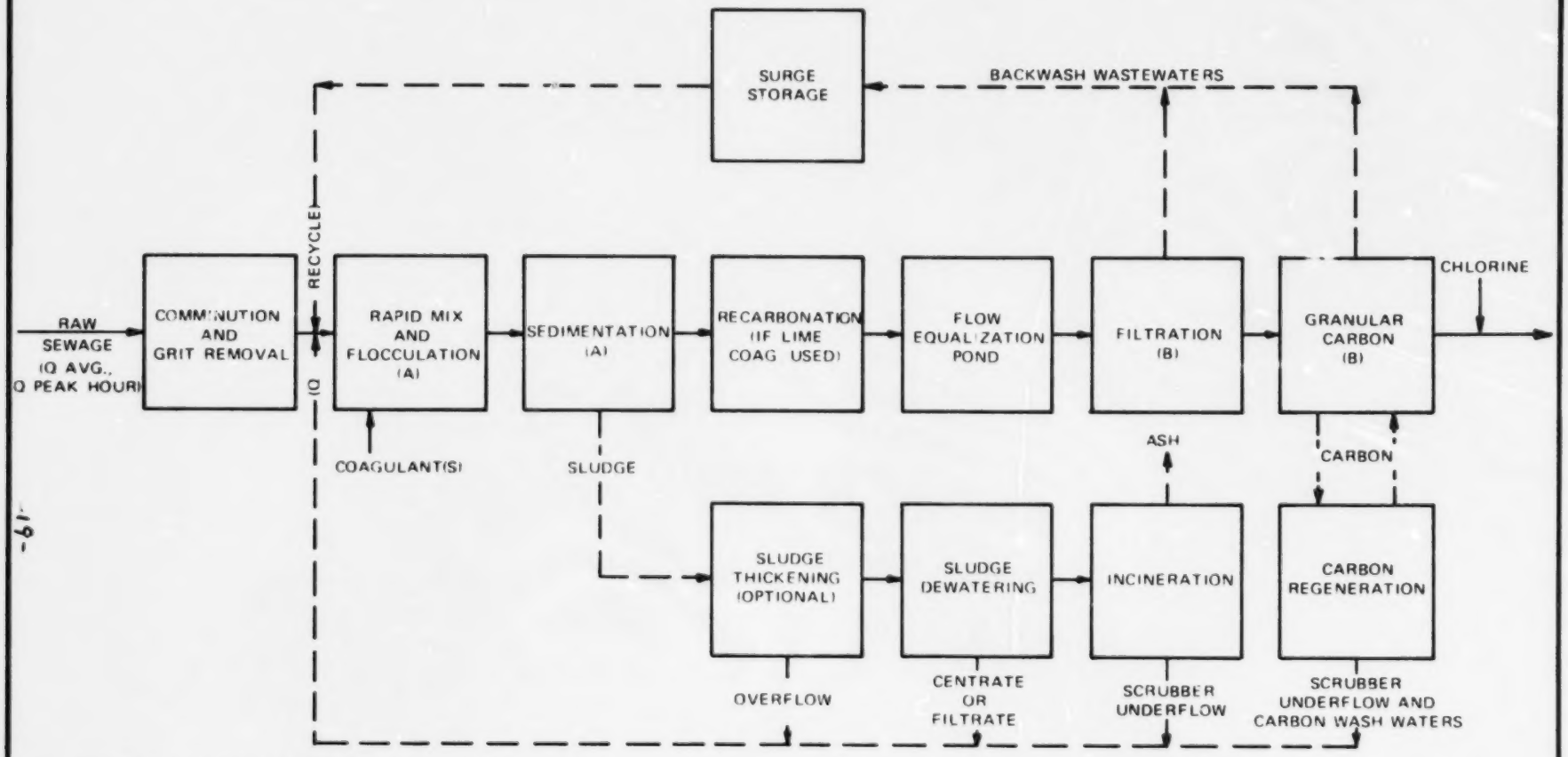


(A) DESIGN FLOW BASED ON Q PEAK HOUR PLUS Q RECYCLE

(B) DESIGN FLOW BASED ON Q AVERAGE PLUS Q RECYCLE.

FIGURE 4

ILLUSTRATIVE SCHEMATIC OF A PHYSICAL – CHEMICAL TREATMENT PLANT

backwash flows, (3) sludge thickener overflow, and (4) sludge dewatering filtrate or centrate. For example, a 15 mgd average flow rate may be associated with a peak hourly rate of 30 mgd. To these values must be added the volume of recycle streams. If these recycle streams total 3.5 mgd in the above example, then the design hydraulic flow rates become 18.5 mgd average and 33.5 mgd peak hour.

Preliminary Treatment

Comminution and grit removal facilities designed in accordance with standard sewage treatment design practices should be provided.

Chemical Feed, Rapid Mix, and Flocculation

These functions may all be carried out in accordance with standard practices followed in the water treatment field for years.

Proper rapid mixing is important to efficient utilization of the coagulating chemicals. The use of a mechanical rapid mixing device in the basins with a total of 2 minutes detention time of the average flow is recommended. When using lime as coagulant, scaling of the mixer shaft will occur and may cause excessive bearing wear if not cleaned regularly. In any case, provision of two parallel rapid mixing units each with a nominal capacity of one-half the design flow is prudent to provide flexibility in operation. Should one mixing unit be down for repair, the entire flow can be passed through the remaining basin which will still provide one minute mixing with the above criteria.

A mechanically mixed flocculator with 15 minutes detention is generally adequate for wastewaters. In many cases, the flocculation resulting from the large coagulant doses added to wastewaters results in very rapid flocculation and even shorter detention

times may be feasible. Provisions should be made to add up to one mg/l polymer at the rapid mix or at the flocculator inlet or outlet or split among these points.

Clarifier Sizing

The critical design parameter is the peak hourly surface overflow rate. Gross carryover of solids can cause the downstream filter or adsorption processes to fail due to excessive headloss which, in turn, will result in a total failure of the plant. Thus, it is of little consolation to know the clarifier will perform properly under average flow conditions only to have a carryover of excessive solids during the peak hourly flow shut the entire plant down. A maximum peak hourly rate of 1,400 gpd/ft^2 for conventional horizontal or radial flow clarifiers is recommended when using lime as a coagulant unless pilot tests indicate that other rates should be used. A maximum average rate of 900 gpd/ft^2 is recommended. Whichever of these two criteria results in the larger clarifier size should be used.

Several attempts have been made to use upflow, sludge blanket type clarifiers on coagulated primary or secondary effluents. Difficulty in holding a sludge blanket has been reported in every case. Successful operation has been achieved with these units by lowering the overflow rate to conventional clarifier rates and eliminating the sludge blanket, which in essence, converts the unit to a conventional radial flow basin. The instability of the sludge blanket or solids contact units is due to the organics found in the raw sewage and the wide variations in incoming flow. These units have been most successful in treating groundwaters of uniform composition at a constant flow rate. The author does not recommend their use on coagulated wastewaters.

Provision should be made for recirculation of controlled amounts of sludge from the bottom of the clarifier to the rapid mix inlet. The high pH of lime-treated water will form deposits of calcium

carbonate on structures and in pipelines which it contacts. Lime sludge suction lines should be glass lined to facilitate cleaning. Provisions must also be made for regular cleaning of all other pipelines which carry the high pH effluent. Use of the new polyurethane cleaning pigs should be compatible with the layout of the pipelines. Mechanical sludge collection equipment used in lime settling basins should be of the bottom scraper type rather than the vacuum pickup style because of the dense sludge to be handled.

Recarbonation

Lime treatment of wastewaters for phosphorus removal often raises the pH to values of 10-11. At this pH, the water is unstable and calcium carbonate floc will precipitate readily. This floc is very tenacious and would encrust any downstream filters or carbon particles to a serious degree. The pH may be lowered by injecting CO_2 gas obtained from the incinerator stack gases. Primary recarbonation is used to reduce the pH from 11 to 9.3, which is near that of minimum solubility for calcium carbonate. In domestic wastewater, primary recarbonation to pH = 9.3 results in the formation of a heavy, rapidly settling floc which is principally calcium carbonate, although some phosphorus is also removed from solution by adsorption on the floc. If sufficient reaction time, usually about 15 minutes in cold water, is allowed for the primary recarbonation reaction to go to completion, the calcium carbonate floc does not redissolve with subsequent further lowering of pH in secondary recarbonation. If lime is to be reclaimed by recalcining and reused, this settled primary recarbonation floc is a rich source of calcium oxide, and may represent as much as one third of the total recoverable lime. If the pH were not reduced to less than about 8.8 before application to the filters and carbon beds, extensive deposition of calcium carbonate would occur on the surface of the grains. This could reduce filter efficiency, and could also drastically reduce the

adsorptive capacity of granular activated carbon for organics. It would produce rapid ash buildup in the carbon pores upon regeneration of the carbon, and would lead to early replacement of the carbon.

It is possible to reduce the pH of a treated wastewater from 11 to 7 or to any other desired value in one stage of recarbonation. Single-stage recarbonation eliminates the need for the intermediate settling basin which is used with two-stage systems. However, by applying sufficient carbon dioxide in one step for the total pH reduction, little, if any, calcium is precipitated with the bulk of calcium remaining in solution, thus increasing the calcium hardness of the finished water, and, in addition, causing the loss of a large quantity of calcium carbonate which could otherwise be settled out, recalcined to lime, and reused. If lime is to be reclaimed or if calcium reduction in the effluent is desired, then two-stage recarbonation is required. Otherwise, single-stage recarbonation may be used with a substantial savings in initial cost, and a reduction in the amount of lime sludge to be handled.

In our example wastewater discussed earlier, there would be no need for two-stage recarbonation because: (1) No reuse of lime is planned. (2) The phosphorus goals can be achieved without the slight additional phosphorus which may be provided by two-stage recarbonation. (3) The low lime dosage required does not add a significant quantity of calcium to the effluent.

If two-stage recarbonation is being considered only for the purposes of lime recovery, one should compare the value of the lime recovered against the cost of providing two-stage recarbonation. Peak hourly overflow rates for the intermediate clarifier in two-stage recarbonation should not exceed 1,400 gpd/ft^2. Provision should be made for polymer addition to the intermediate clarifier influent.

The details of design for recarbonation systems may be found in Advanced Wastewater Treatment.

Filtration

Whether or not filtration is needed prior to activated carbon adsorption is subject to debate. There is no question that filtration ahead of a downflow granular carbon adsorption bed will reduce the rate at which the pores of the activated carbon become plugged with inert materials. Also, the use of an efficient filter permits downstream use of upflow, packed carbon beds which may be operated in the more efficient countercurrent mode discussed later. The question is whether or not the cost of providing the filtration exceeds the benefits mentioned above. Only long-term operating data from plants using granular carbon with and without prior filtration will answer this question. In the interim, a conservative design will include filtration prior to carbon adsorption. In addition to protecting carbon pores from plugging by inerts, mixed media filtration also provides a more efficient means of solids removal than carbon alone, resulting in a higher effluent quality. Filtration equipment is available which will provide simple, reliable, and automatic operation. Carbon is not a particularly effective filter because it acts as basically a surface type filter and as such, is subject to all the shortcomings of other surface filters applied to wastewaters. Any high solids loading will blind a surface type filter in short order. The use of dual media or mixed, tri-media filters provides a much more efficient filtration device which is capable of tolerating a much higher solids loadings than is a surface type filter. A discussion of alternate filtration devices and a detailed discussion of filter system design may be found in Advanced Wastewater Treatment.

In instances where an upflow expanded bed carbon contactor is used, the filter may be located downstream of the carbon column to remove the bacterial floc which is flushed from the carbon.

For the removal of the trace amounts of chemical floc which one will expect from the chemical clarifier, a properly designed dual media or mixed tri-media bed may operate at rates of 5-10 gallons per minute per square foot. The use of 5 gpm/ft^2 will provide a conservative basis for design. Surface wash is a must when filtering sewage. The author's experience with air-water wash techniques and hydraulic surface wash technique is that the water savings with the air techniques are insignificant, if they exist at all, and the hydraulic surface wash offers a much simpler technique. The remaining question is whether the filter structure should be of the gravity or pressure type. The pressure system offers significant advantages in wastewater applications. In many instances, the applied solids loading will be higher and more variable than in a water treatment application. Thus, it is desirable to have higher head available than practical with gravity filter designs, preferably up to 20 feet of head when operating at 5 gpm/ft^2. In many physical-chemical treatment processes, the filtration step will be followed by a granular carbon adsorption step. The filter effluent from the pressure filter can pass through the downstream carbon columns without having to be repumped, often eliminating a pumping step which would be required with a gravity filter. All filter wash waters must be reprocessed in sewage applications. The use of the pressure filter will reduce the amount of wash water because of its ability to operate to higher head losses.

The backwashing of the filter is accomplished by reversing the flow at a rate of 3-4 times the normal through-put rate of 5 gpm/ft^2. Direct return of the wash waters directly to the head of the plant would create a very substantial hydraulic surge which may cause the upstream clarifier to fail. Therefore, the backwash wastewater should be collected in a storage tank and recycled to the head of the plant at a controlled rate. The surge storage tank should be sized adequately to handle successive backwashes from two or three filters.

It is desirable to precede the filtration step with a flow equalization pond so that the filters may be operated at essentially a constant rate. Provisions should be made for a feed of polymer directly to the filter influent as a filter aid. Filter effluent turbidity and head loss should be monitored continuously with high filter head loss being used to initiate an automated backwash program.

Granular Carbon Adsorption

Because of the unproven economics of recovery and reuse of powdered carbon, the use of granular carbon is the only current practical technique available for removal of soluble organics from coagulated raw wastewater. Chemical oxidation techniques are not yet practical for the large quantities of organics involved. The major design decisions facing the engineer is the selection of a contact time (30 minutes in the example discussed earlier), what dose of carbon is required (can be conservatively estimated by assuming a removal of 0.5 pounds of COD per pound of carbon prior to regeneration) and the configuration of carbon contactor to be used. Typically, the carbon doses will be substantially higher than when granular carbon is applied to coagulated and filtered secondary effluent. In the earlier example, a carbon dose of slightly more than 1,000 pounds per million gallons was estimated. This magnitude of dose is not unusual when applying carbon to coagulated raw sewage.

Contact times of about 30 minutes have been reported by many investigators as marking the point of diminishing returns. That is, a drastically longer contact time would not provide any proportionately greater removal of organics.

The two major alternate contactor configurations to consider are open concrete vessels of either an upflow or downflow type or upflow, counter-current columns in steel vessels. The counter-current approach (see Figure 5) offers a more efficient utilization

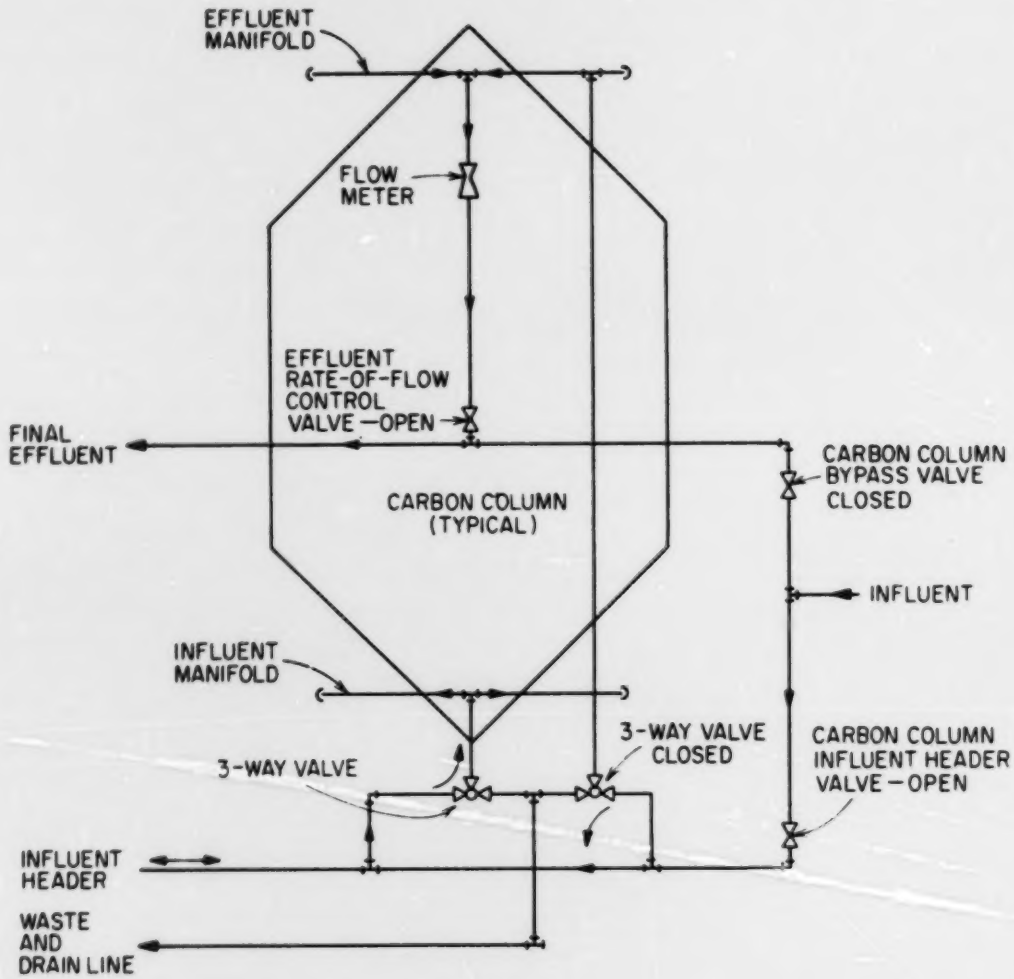
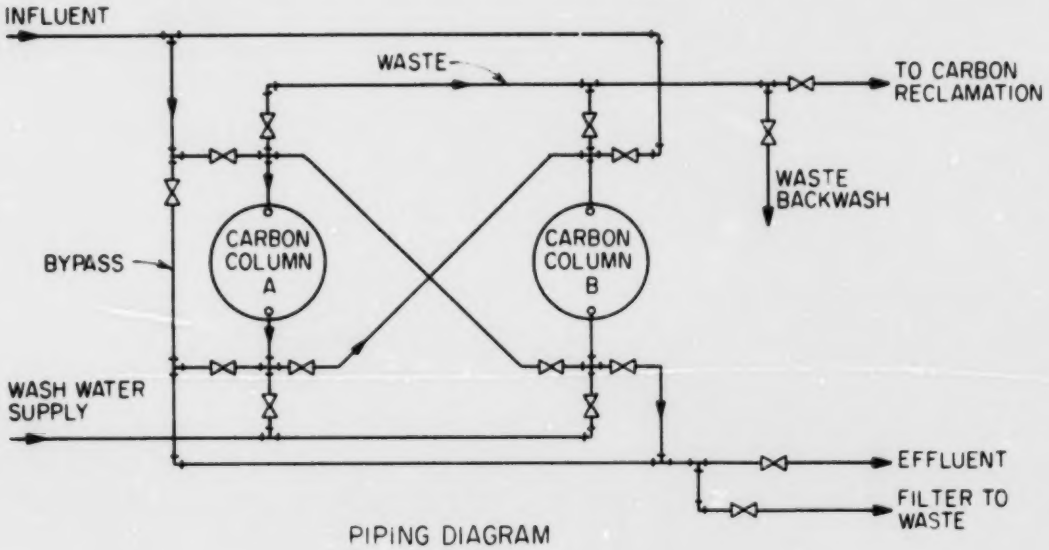


FIGURE 5

TYPICAL ARRANGEMENT FOR UPFLOW, COUNTER CURRENT CARBON CONTACTOR
(FROM CULP & CULP)

of the carbon as only the most saturated carbon is withdrawn for generation. This results from the fact that as the carbon becomes saturated with organics, it becomes heavier. When the carbon column is backwashed, the more saturated, heavier carbon migrates to the bottom of the column where it is withdrawn for regeneration. A semi-counter-current approach can also be achieved by using two downflow columns in series. As indicated on Figure 6, water is first passed down through Column A then down through Column B. When the carbon in Column A is exhausted, the carbon in Column B is only partially spent. At this time, all carbon in Column A is removed for regeneration, and is replaced with fresh carbon. Column B then becomes the lead column in the series. When the carbon in Column B is spent, the carbon is removed for regeneration and is replaced with fresh carbon. This type of operation gives only some of the advantages of counter-current operation, because only the carbon near the inlet of the lead bed is fully saturated with impurities removed from the water, and some capacity is unused in much of the rest of the carbon sent to regeneration. Also, the piping and valving is more complex and costly than for an upflow, counter-current column. Unless one is attempting to use the carbon for the dual purpose of filtration and adsorption (which the author does not recommend for most cases), there is no advantage to using the downflow approach while there are the disadvantages discussed above.

The choice of contactor design is also dependent upon the method selected for control of hydrogen sulfide generation in the carbon columns. The upflow, expanded bed with a downstream filter has been used with injection of oxygen into the carbon influent for hydrogen sulfide control. The prolific biological growth resulting from this approach would result in excessive head loss in a downflow, packed bed. Frequent backwashing of a downflow, packed bed has been reported effective at Rocky River in controlling hydrogen sulfide. Also, breakpoint chlorination, prior to downflow beds, although expensive, has been reported effective



PIPING DIAGRAM

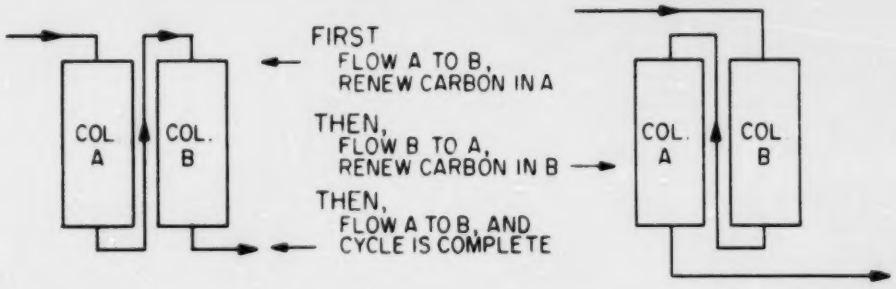


FIGURE 6

TWO DOWNFLOW CARBON CONTACTORS IN SERIES
(FROM CULP & CULP)

at Blue Plains in controlling hydrogen sulfide. Higher operating pressures and hence, greater carbon depths may be used in steel pressure contactors. As a result, a concrete contactor generally has a shallower carbon depth and a greater surface area of carbon to maintain the same contact time. Thus, there is substantially more underdrain area and influent and effluent headers per unit of contact time in the gravity concrete structures. Economic comparisons between the two approaches show that there is not a great deal of cost difference in most cases. The technology transfer manuals published by EPA and Advanced Wastewater Treatment present detailed carbon contactor design alternates. Also, the next paper by Rizzo on this program will discuss design of alternate carbon contactor designs in detail. However, there are a few other points related to contactor design which I would like to call to your attention in addition to the comments above. When using steel contactors, it is imperative that the interior be properly protected from the very corrosive effects of partially dewatered activated carbon. Two 8-mil thick coatings of a coal tar epoxy has proven to be effective at Tahoe over 4 years of continuous operation. Fiberglas-polyester coatings would also be effective, although more costly than the coal-tar epoxy coatings. Costs for shop-applied coatings will vary from about $\$0.50/ft^2$ to $\$2.00/ft^2$ depending upon the material and thickness selected. Costs for field applied coatings will be about twice as high. Also, in most cases, the costs of fabricating steel vessels in the field will be substantially higher per pound of steel than for a shop fabricated vessel.

Another point to consider is the effect of the pH of the upstream coagulation step on the efficiency of the carbon process. One available process is based on a claim that use of extremely high pH in the lime coagulation process will hydrolyze some organic materials making them more readily adsorbable. The author has attempted to duplicate these results on six different wastewaters with no attributable benefit associated with using a high pH of coagulation. Thus, before one incurs the disadvantages of the

high pH approach (massive quantities of sludge plus greatly increased carbon dioxide requirements for pH adjustment), one should carefully evaluate the effects of pH on the specific wastewater involved.

Carbon Regeneration

As granular activated carbon adsorbs organics from wastewater, the carbon pores eventually become saturated and the carbon must be regenerated for reuse. The best way to restore the adsorptive capacity of the carbon is by means of thermal regeneration. By heating the carbon in a low-oxygen steam atmosphere in a multiple-hearth furnace at temperatures of 1,650-1,750 degrees F, the dissolved organics are volatilized and released in gaseous form. The regenerated carbon is cooled by water quenching. By proper treatment, carbon can be restored to near virgin adsorptive capacity while limiting burning and attrition losses to 5-10 percent. Regeneration furnace off-gas odors can be controlled by afterburning, if necessary, and particulates and soluble gases can be removed by use of Venturi or jet impingement type scrubbers. Figure 7 illustrates a typical regeneration system.

The carbon furnace should be sized with recognition of the fact that substantial downtime may be required for maintenance of the furnace. An allowance of 40 percent downtime in selecting the furnace size provides a conservative basis for furnace selection. Details on the design and operation of carbon regeneration systems may be found in Advanced Wastewater Treatment.

SUMMARY

Relatively simple techniques for determining the efficiency of physical-chemical treatment of a given wastewater are available and are described. A brief discussion of design criteria for the major unit processes is presented.

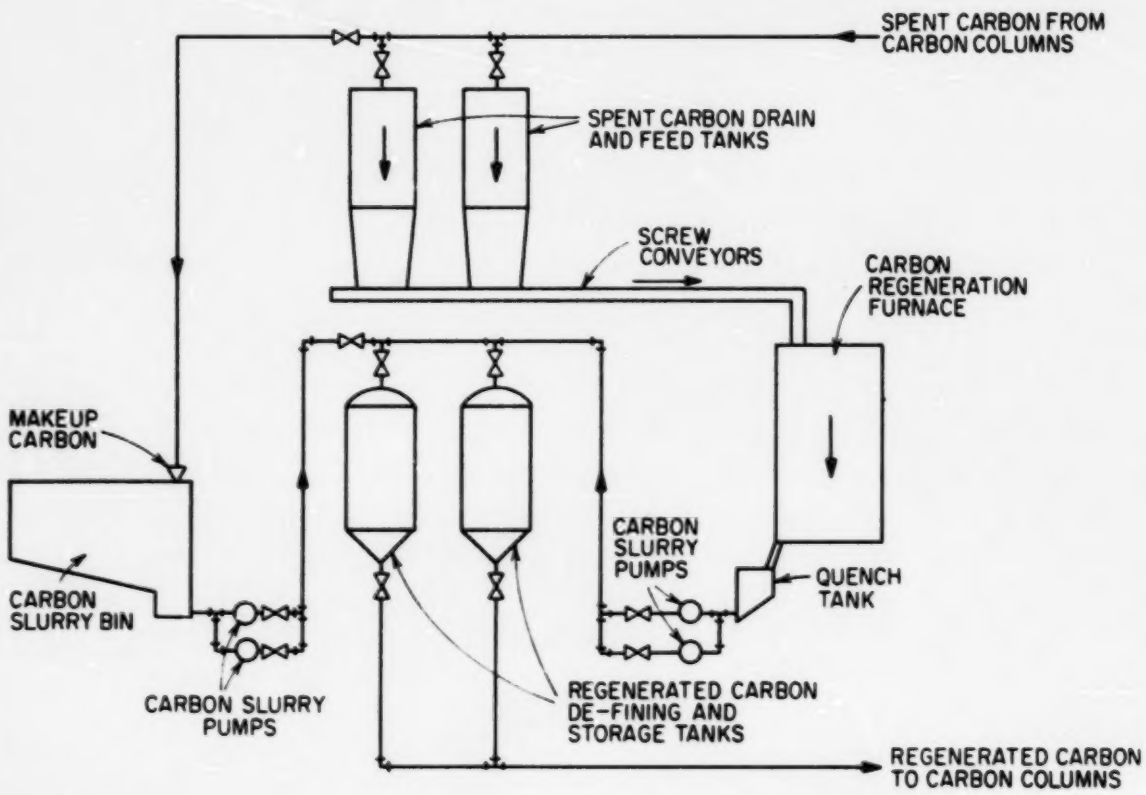


FIGURE 7

ILLUSTRATIVE CARBON REGENERATION SYSTEM
(FROM CULP & CULP)

REFERENCE

Culp, R. L. and Culp, G. L.; "Advanced Wastewater Treatment" Van Nostrand Reinhold Co.; New York, New York (1971).